strength which results from such a structure, has been abundantly demonstrated by Mr J. W. Spencer of Newcastle.

The effect of annealing and tempering is, in fact, very complicated, as is shown by the long series of researches which Barus and Strouhal have conducted. They consider that annealing is demonstrably accompanied by chemical change even at temperatures slightly above the mean atmospheric temperature, and that the "molecular configuration of glass-hard steel is always in a state of incipient change . . . . a part of which change must be of a permanent kind." Barus considers[1] that glass-hard steel is constantly being spontaneously "tempered" at the ordinary temperature, which, he says, "acting on freshly quenched [that is, hardened] steel for a period of years, produces a diminution of hardness about equal to that of 100° C. acting for a period of hours."

The nature of the molecular change is well indicated in the long series of researches which led them to conclude that in steel "there is a limited interchange of atoms between molecules under stress, which must be a property common to solids if, according to Clerk-Maxwell's conception, solids are made up of configurations in all degrees of molecular stability."

Barus and Strouhal attach but little importance to the change in the relations between the carbon and the iron during the tempering and annealing of hard steel. They consider that in hardening steel the "strain once applied to steel is locked up in the metal in virtue of its viscosity"; tempering is the release of this molecular strain by heat.

Highly carburised steels harden very energetically by very slight modifications in thermal treatment, and it will be evident that a very hard material is unsuitable for industrial use if the conditions of its employment are such as to render it desirable that the material should stretch.

To turn to the class of steel which does not harden, it is certain that, although wrought iron passes almost insensibly into steel, there can be no question that, not merely the structural, but the molecular aggregation of even steel containing only $\frac{2}{10}$ per cent. of carbon is profoundly different from that of wrought iron. The class of steel which was formerly employed for weapons and tools belonged to the highly carburised, readily hardening class. It was the "mild steel," containing but little carbon, which was destined to replace wrought iron; and when attempts were made to effect the general substitution of steel for iron, fears as to its character and trustworthiness unfortunately soon arose, so that from about the year 1860 until 1877 steel was viewed with suspicion. This can now be explained. Doubts as to the fidelity of steel, even when it was obtained free from entangled cinder, arose from ignorance of the fact that, on either side of a comparatively narrow thermal boundary, the physical

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[1] *Phil. Mag.*, vol. xxvi. (1888), p. 209.

properties of iron and steel may vary greatly. The steel was "true" enough, but, from the point of view of the special duties to be entrusted to it, its fidelity depended largely on the heat treatment it had received. Artificers attempted to forge steel after it had cooled down below the point *a* of Chernoff at which recalescence occurs, and they often attempted to work highly carburised steel at insufficiently low temperatures.

Classification of Steel.—From the foregoing remarks, it will be evident that the use of steel depends largely upon its power of being hardened and tempered. At the same time it must not be imagined that all steel is hardened and tempered before use. The greater proportion of what is known as steel is used in the condition in which it leaves the rolls. This includes all mild steel used for structural purposes, boiler-plate, and steel rails. It may not be out of place, therefore, to indicate the way in which steel may be classified from the point of view of its industrial use, according to the amount of carbon it contains. Steels may be grouped under certain definite percentages of carbon, ranging from 0·1–1·5 per cent. Each class merges into the other, but the members at either end of the series vary very greatly. A sharp razor cannot be made from boiler-plate, and razor steel is unsuited for making a boiler that will resist high temperature when overheated.

The steel used for naval construction contains 0·15–0·2 per cent. of carbon. When steel faces are used for the armour-plates, the material contains 0·7–0·8 per cent. of carbon.

With regard to steel used in civil engineering, the most remarkable case is presented by the Forth Bridge. The steel of which the compression members of the structure are composed contains 0·23 per cent. of carbon and 0·69 per cent of manganese. The parts subjected to extension do not contain more than 0·19 per cent. of carbon.[1]

Steel rails contain from ·35–·55 per cent. of carbon, and in this class slight variations in the amount of carbon are of considerable importance, as in certain climates a variation of 0·1 per cent. in the amount of carbon may be very serious. The great benefit which has accrued to the country from the substitution of more durable steel rails for the old wrought-iron ones may be gathered from the statement of Webb of Crewe, which shows that "the quantity of steel removed from the rails throughout the London and North-Western system by wear and oxidation is about 15 cwts. an hour, or 18 tons a day."

Gun-steel contains 0·3–0·4 per cent. of carbon, and it may contain 0·8 per cent. of manganese. It is in relation to gun-steel that oil hardening becomes very important. The oil tank of the Saint-Chamond Works (on the Loire) is 72 feet deep, and contains 44,000 gallons of oil, which is kept in circulation by rotary

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[1] *Journ. Iron and Steel Inst.*, vol. ii. (1888), p. 94.

pumps to prevent the oil being unduly heated locally when the heated mass of steel is plunged into it.

The most formidable projectiles belong to the highly carburised class of steel. Shells contain 0·8–0·94 per cent. of carbon, and, in addition, some of these have up to 2 per cent of chromium. The firm of Holtzer showed in the Paris Exhibition a shell which pierced a steel plate 10 in. thick, and was found, nearly 800 yds. from the plate, entire and without flaw, its point alone being slightly distorted.

Lastly, reference must be made to the highly carburised steel used for the manufacture of dies. Such steel should contain 0·8 to 1 per cent. of carbon and little manganese. It is usual to water-harden and temper it to a straw colour, and a really good die will strike 40,000 coins of average dimensions without being fractured or deformed; and if the steel contain 0·1 per cent. too much carbon, it would not strike 100 pieces without cracking; and if it contained 0·2 per cent. too little carbon, it would probably be hopelessly distorted and its engraved surface destroyed in the attempt to strike a single coin.

The above examples will be sufficient to show how diverse are the properties which carbon confers on iron, but, as Faraday said in 1822, "it is not improbable that there may be other bodies besides charcoal capable of giving to iron the properties of steel." The strange thing is that it is not known with any certainty whether, in the absence of carbon, other elements do play the part of that metalloid in enabling iron to be hardened by rapid cooling. Take the case of chromium, for instance; chromium-carbon steels can, as is well known, be energetically hardened, but Busek[1] has asserted that the addition of chromium to iron in the absence of carbon does not enable the iron to be hardened by rapid cooling. Probably by employing the electrical method of heating adopted by Pepys a decision will be arrived at as to the hardening properties of elements other than carbon.

A few words must be devoted to the consideration of the colours which direct the artist in tempering or reducing the hardness of steel to any determinate standard. The technical treatises usually give, not always accurately, as Reiser[2] has shown, a scale of temperature ranging from 220° to 330°, at which various tints appear, passing from very pale yellow to brown-yellow, purples, and blues to blue tinged with green, and finally to grey. Barus and Strouhal point out[3] that it is possible that the colour of the oxide film may afford an indication of the temper of steel of far greater critical sensitiveness than has hitherto been supposed. How far time, temperature, and colour are correlated is uncertain.

That the colours produced are really due to oxidation was

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[1] *Stahl und Eisen*, vol. ix. (1889), p. 728.

[2] *Das Härten des Stahles*, p. 78 (Leipzig, 1881). See also Loewenherz, *Zeitschrift für Instrumentenkunde*, vol. ix. (1889), p. 322.

[3] *Bull. U.S. Geo. Survey*, No. 27 (1886), p. 51.

shown by Sir Humphry Davy in 1813,[1] but the nature of the film has been the subject of much controversy. Barus points out that "the oxygen molecule does not penetrate deeper than a few thousand times its own dimensions," and that it probably passes through the film by a process allied to liquid diffusion. The permeable depth increases rapidly with the temperature until, at an incipient red heat, the film is sufficiently thick to be brittle and liable to rupture. A table of temperatures corresponding to colour tints is given by Howe.[2]

Summary.—Looking back over all the facts dealt with on the thermal treatment of steel, it will be evident that two sets of considerations are of special importance—(1) those which belong to the relations of carbon and iron, and (2) those which contemplate molecular change in the iron itself. The first of these has been deliberately subordinated to the second, although it would have been possible to have written much in support of the view that carburised iron is an alloy of carbon and iron, and to have traced, with Guthrie, the analogies which alloys, in cooling, present to cooling masses of igneous rocks. This view has been developed with much ability by Howe,[3] whose suggestion of mineralogical names such as "cementite," "pearlite," and "ferrite" for the various associations of carbon and iron is now generally adopted.

Such analogies present considerable interest, but the possibility of molecular change in the iron itself, which results in its passage into a distinctive form of iron, is at present an important subject for consideration, not merely in relation to iron, but as regards the wider question of allotropy in metals generally.

Many facts noted in spectroscopic work will, as Lockyer has shown, have indicated the high probability that the molecular structure of a metal like iron is gradually simplified as higher temperatures are employed. These various simplifications may be regarded as allotropic modifications.

The question of molecular change in solid metals demands continued and rigorous investigation. It is well known what important discoveries have been made in chemistry by the recognition of the fact that the elements act on each other in accordance with the great law of Mendeléef, which states that the properties of the elements are periodic functions of their atomic weights. There is little doubt but that it will be shown that the relation between small quantities of elements and the masses in which they are hidden is not at variance with the same law.

The future of steel will depend on the care with which the nature of the influence exerted by various elements on iron is

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[1] Sir Humphry Davy, *Thomson's Ann. Phil.*, vol. i. (1813), p. 131, quoted by Turner, *Proc. Phil. Soc. Birmingham*, vol. vi. (1889), part ii.

[2] Howe, *Metallurgy of Steel*, p. 23 (1890).

[3] *Engineering and Mining Journal*, vol. xlvi. (1888), p. 131. See also *The Metallurgy of Steel*, vol. i. (New York, 1890), p. 165.

investigated, and by ascertaining the thermal treatment to which it may most suitably be subjected.

Thermal Treatment of Industrial Alloys.—Although the great changes made possible by slightly varying the thermal treatment of steel are not found to the same extent in non-ferrous alloys, yet it is recognised that very valuable properties may be induced in various alloys by correct heat treatment. The correct temperature for casting is an important point and has been studied by Longmuir,[1] who found, in the case of brasses and bronzes, that the tenacity, ductility, and contraction of area increase as the temperature of casting decreases from a high temperature to a fair casting heat, and that, on further cooling down before casting, a distinct fall in mechanical properties results. Gun-metal and Muntz metal cast at lower temperatures were found to be mechanically better than those cast at higher temperatures, whereas in the case of yellow and red brasses a high-temperature cast was found to be better than a low-temperature cast. The following table illustrates this point:—

Alloy.	No.	Casting Temperature.	Elastic Limit. Tons per Sq. In.	Maximum Stress. Tons per Sq. In.	Extension on 2 ins. Per cent.	Reduction of Area. Per cent.
Gun-metal .	1	1173	6·468	8·376	5·5	4·23
	2	1069	8·482	14·838	14·5	16·71
	3	965	8·984	11·018	5·0	6·36
Yellow Brass	1	1182	4·432	11·484	37·75	31·40
	2	1020	3·974	12·713	43·00	35·66
	3	850	4·150	7·447	15·00	15·25
Red Brass .	1	1308	4·284	6·855	13·25	12·65
	2	1073	4·263	12·649	26·00	30·28
	3	1058	4·376	5·670	5·5	6·64
Muntz Metal	1	1038	8·753	12·454	6·0	10·60
	2	973	9·637	18·889	15·0	16·10
	3	943	9·526	16·287	9·5	14·81

The importance of casting temperature is also illustrated by the following figures of an aluminium-copper alloy containing 4·63 per cent. of copper,[2] showing that the tenacity and ductility are greatly decreased by even small increases in the casting temperature:—

Casting Temperature.	Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elongation on 2 ins. Per cent.
650°	5·6	9·68	8·5
724	5·0	7·04	5·5
707	4·5	4·89	3·0

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[1] *Journ. Iron. and Steel Inst.*, 1903, i. p. 457.

[2] *Proc. Inst. Mech. Eng.*, 1907, p. 92.

Sand Casting and Chill Casting.—The rate at which the metal cools down after casting is found to make a considerable difference in the mechanical properties of some alloys. In ordinary sand casting the metal cools down fairly slowly, whereas when a chill is introduced, in the form of an iron mould for casting, the cast solidifies much more quickly, especially on the surface, and valuable properties are thus induced. In the case of copper-aluminium alloys up to 9 per cent. of aluminium the chill castings gave somewhat better mechanical tests; and at the other end of the series, aluminium alloys containing up to 6 per cent. of copper, chill castings are superior to sand castings, both in strength and ductility.

Effect of Annealing Alloys.—The aluminium bronze containing 9·9 per cent. Al was found to be very sensitive to heat treatment,[1] the results of mechanical tests showing that profound changes take place between 300° and 400°; for after annealing at 300° the tests are practically the same as those of rolled bars, whereas after annealing at 400° there is shown a rise of nearly 100 per cent. in the elastic ratio, due to an increase in yield point and a decrease in ultimate stress, and it will be seen from the following table that the ductility has dropped almost to *nil*; the fractures also are found to be characteristically different. It is somewhat surprising that these changes in mechanical properties are not accompanied by differences in microscopic structure, the etched surface appearing very similar to that obtained with the rolled bar. On annealing at 800° and 900° there is a further loss of strength; the fracture becomes coarsely crystalline, and the etched surfaces of specimens heated in this range show considerable structural alterations.

EFFECT OF ANNEALING ALUMINIUM BRONZE (9·9 per cent. Al).

Treatment.	Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elastic Ratio.	Elongation.- Per cent. on 2 ins.	Reduction of Area. Per cent.
Bar as rolled . .	14·8	38·1	·39	28·8	30·80
Annealed 1 hour at 300°	14·6	38·04	·38	27·0	33·06
,, ,, 400	23·4	31·69	·74	2·5	2·86
,, ,, 500	20·5	34·08	·60	9·5	13·11
,, ,, 600	15·7	31·74	·50	9·0	14·50
,, ,, 700	15·1	31·85	·48	9·0	11·25
,, ,, 800	12·7	26·23	·48	13·5	21·60
,, ,, 900	13·3	21·95	·61	6·0	8·76

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[1] *Proc. Inst. Mech. Eng.*, 1907, p. 178.

Effect of Quenching Aluminium Bronze at various Temperatures. — When the alloy containing 9·9 per cent. Al is quenched in water from various temperatures above 600°, a rise in yield point and ultimate stress is obtained, with a corresponding fall in elongation and reduction of area, the results being most pronounced above 800°, as will be seen from the following table :[1]—

EFFECT OF QUENCHING ALUMINIUM BRONZE (9·9 per cent. Al).

Quenching Temperature.	Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elastic Ratio.	Elongation on 2 ins. Per cent.	Reduction of Area. Per cent.
600°	17·0	38·18	0·45	22·2	30·00
700	18·1	39·76	0·46	15·4	20·60
800	32·4	43·57	0·75	7·0	14·29
900	39·8	51·51	0·77	3·0	4·83

Effect of Annealing Muntz Metal.—The effect of annealing Muntz metal (Cu 60, Zn 40) at different temperatures and for different lengths of time has been studied by Bengough and Hudson,[2] and from their paper the following table is copied, showing that the general effect of annealing this alloy is to reduce the ultimate stress and increase the elongation.

Temperature of Annealing.	Time.	Ultimate Stress. Tons per Sq. In.	Elongation on 2 ins. Per cent.
As cast	...	23·4	17·1
As rolled	...	30·2	37·7
310°	7 hours	28·6	43·0
335	7 days	27·4	45·1
410	7 hours	27·4	48·0
490	7 ,,	26·1	56·0
540	7 ,,	24·4	57·7
685	7 ,,	23·5	53·5

Effect of Mechanical Work on the Properties of Alloys.—The mechanical tests of some alloys are very much improved by work, *e.g.* rolling or drawing, with or without annealing, and a very good example of this is found in the case of aluminium alloys containing from 0–8 per cent. Cu; all these alloys roll well, and from 0–4 per cent. Cu they draw sound also. These alloys

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[1] *Proc. Inst. Mech. Eng.*, 1907, p. 173.
[2] *Journ. Soc. Chem. Ind.*, xxvii., 1908, pp. 43 and 654.

require a considerable amount of mechanical work in order to get the full value of their inherent properties, and the following table[1] illustrates the beneficial effect on an alloy containing 3·76 per cent. Cu :—

Conditions.	Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elastic Ratio.	Elongation on 2 ins. Per cent.	Reduction of Area.
Chill casting . .	5·4	9·60	0·56	10·5	21·46
$1\frac{1}{4}$-in. rolled bar .	9·0	16·83	0·54	20·0	38·21
$\frac{13}{16}$,, ,, .	11·6	17·00	0·68	21·0	49·76
$\frac{13}{16}$-in. bar drawn with annealing . .	15·5	16·90	0·92	8·0	21·79
$\frac{29}{32}$-in. bar drawn without annealing	18·5	20·00	0·92	7·5	20·84

The improvements effected in yield point and in the case of the $1\frac{1}{4}$ and $\frac{13}{16}$ in. rolled bars in reduction of area are particularly noticeable and important; and as this is an alloy whose specific gravity is only 2·79, it may be found very useful where a combination of lightness and strength is desired, and is worth further investigation.

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[1] *Proc. Inst. Mech. Eng.*, 1907, p. 245.

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Special Note on Constituents of Steel.—The Congress of the International Association for Testing Materials have recently (Sept. 1909) adopted a series of definitions of the constituents of steel from which the terms *Troostite* and *Sorbite* were omitted, but in which the constituent which is present in hardened and tempered steels as an intermediate stage between *Martensite* and *Pearlite* is defined under the name *Osmondite*.